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Investigation of Flight Data Recorder Fire Test Requirements

Lawrence J Curran, Jr.

October 1994
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16. Abstract

This report evaluates fire test methodologies for aircraft flight data and cockpit voice recorders. The current fire test requirement consists of a 30-minute exposure to a propane burner calibrated to the heating conditions created by a jet fuel fire. A comparison was made of the internal temperature of flight recorder models subjected to the propane burner standard and a jet fuel fire. The internal temperature was approximately 40 percent higher during the fuel fire tests which were 6-8 minutes in duration. Although the fuel fire duration was limited, it appears that a 60-minute propane burner test exposure is a feasible and conservative means of evaluating the thermal resistance of a flight recorder subjected to a 30-minute fuel fire. An additional fire test condition (500°F/10 hours) has been proposed to simulate a smoldering fire which may persist for a long period of time at a remote site. A state-of-the-art magnetic tape of the cockpit voice recorder was subjected to this condition in an oven and failed the test, demonstrating the severity of this exposure environment.

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INTRODUCTION

PURPOSE.

The purpose of this project was to determine a realistic thermal profile and test protocol for improved flight data recorder and cockpit voice recorder fire test requirements that reflect the actual environment of post-impact fires. The project was structured to examine both the high-intensity fuel fire as well as the longer-duration, low-temperature smoldering or natural fuel fed fire.

BACKGROUND.

As defined in the Code of Federal Regulations Part 14, Subsection 121.343 (14CFR121.343), no person shall operate a large airplane that is certified for operations above 25,000 feet altitude or is turbine powered unless it is equipped with one or more approved flight data recorders (FDR) capable of recording certain specified parameters. In addition, 14CFR121.359 states that no person shall operate a large turbine engine powered airplane or a large pressurized airplane with four reciprocating engines unless an approved cockpit voice recorder (CVR) is installed and operated for the duration of flight including the preflight and post-flight checklist activities. Approved flight recorders are defined in Technical Standard Orders (TSO) C51a and C124.

Approved cockpit voice recorders are defined in TSO's C84 and C123. These TSO's provide the minimum performance standards that must be exhibited by the recorders to be certified for use, including the fire protection requirements.

The National Transportation Safety Board (NTSB) has analyzed the survival history of flight and voice data recorders. During the period from 1966 through March of 1992 there were a total of 90 flight and voice data recorders known to have sustained some degree of thermal damage due to postcrash fires. Of these 90 recorders, 42 (or 47 percent) were exposed to such a degree that the magnetic tape medium was either damaged or destroyed. Moreover, in the more recent time period of March 1989 through March 1992 alone, there were six accidents where vital flight recorder information was lost as a result of the postcrash fire. Based on these findings, on May 28, 1992, NTSB sent a letter to the Acting FAA Administrator containing four specific recommendations related to the fire protection requirements of flight and voice data recorders. One of these recommendations A-92-46, was assigned a Class II Priority Action status and read as follows:

> Conduct a study, based on accident case histories, to determine a realistic thermal profile and test protocol for improved flight recorder fire test requirements that reflect the actual environment of post-impact fires.

This project was undertaken as the result of this recommendation.

DISCUSSION

TEST PLAN.

The test plan was divided into four discreet phases. Phases I and II dealt with the adequacy of the short-term, high-intensity fire test which is currently defined as exposure of 100 percent of the recorder surface to a flame measuring at least 1100 degrees Centigrade (measured 1 inch from the recorder surface) and having a thermal flux of not less than 50,000 British Thermal Units/foot squared-hour (Btu/ft ^{2}-hr), or 158 Kilowatt/meter squared (kW/m ^{2}). Phase III and Phase IV dealt with the longer term low-temperature exposure following a crash and initial burn-off of the fuel. The phases were as follows;

PHASE I. This phase consisted of a series of 11 full-scale fuel fires tests conducted indoors to assure repeatable fire exposure conditions. Utilizing a water calorimeter depicted in figure 1, a dry insulated box depicted in figure 2, and a solid steel slug calorimeter depicted in figure 3, these tests defined the heating conditions a CVR/FDR would be exposed to in a postcrash fuel fire environment. Other instrumentation utilized in this series consisted of chromel-alumel Type K thermocouples and a Gardon gauge total heat flux calorimeter. This phase also provided data that were used to determine the validity of the absorption constant that is utilized in paragraph A5.1.4f of the document ED56A, prepared by the European Organization EUROCAE (reference 1). This document has defined the state-of-the-art crash/fire survival test standards for flight recorders. ED56A states that an absorption constant of 0.5 may be assumed for recorders with a painted steel, stainless steel, or titanium outer case unless other evidence is available.

PHASE II. This phase consisted of a series of small-scale propane burner tests, following the procedures specified in ED56A. Utilizing the same water calorimeter, dry box, and slug calorimeters as in phase I, these small-scale tests attempted to replicate the heating conditions achieved in the full-scale fuel fires of phase I. As with phase I, the data gathered was used to determine the validity of the 0.5 absorption constant utilized in ED56A. This phase also provided a comparison of the thermal exposure experienced by a flight recorder in the current certification test and a real fuel fire.

PHASE III. This phase attempted to define limits for the thermal profile that a recorder would be subjected to in the postcrash environment following the extinction of the fuel fire when the accident occurs in a remote area with a dense population of natural materials such as a forest or jungle. A literature search was made to find data on the temperatures and heat flux generated by a large natural fuel fire. Work has been done in this area by the U.S. Forest Service at their Pacific Southwest Forest & Range Experiment Station. Consideration was given to performing large-scale tests to simulate an initial fuel fire followed by a long-duration natural fuel fire. However, the data found in the literature was deemed to be sufficient to establish an upper boundary on the expected temperatures that may persist in a smoldering fire fed by natural materials.

PHASE IV. This phase consisted of a series of tests conducted in an oven. Using data obtained in phase III and that supplied from several vendors, a repeatable, conservative, long-duration, low-temperature oven test was evaluated. The test conditions were developed by Working Group 18 of EUROCAE and included the requirement for a 10-hour exposure at a temperature of 260°C.

TEST ARTICLES AND FACILITIES.

The phase I tests were conducted in the Full-Scale Fire Test Facility (Bldg. 275). An existing 8- by 10-foot fire pan located adjacent to a Boeing 707 fuselage was filled with approximately 55 gallons of JP4 aviation kerosene and the fuel was ignited. The three test articles, illustrated in figures 1, 2, and 3, were employed to characterize the fire threat. Only one test article was used in each test. Each test article was positioned in the center of the pan and elevated 3 feet above the pan surface on a steel platform. The test setup is shown in figure 4. The location of the test article in the fuel pan ensured that the test article was fully engulfed in flames for the duration of the test. Each test utilized Type K thermocouples and some tests also included a Gardon gauge calorimeter to measure fuel fire temperature and heat flux, respectively. The instrumentation was routed to a combined Omega/Data General data acquisition system which stored all data and displayed it in both graphical and tabular form. The fires were approximately 10 minutes in duration, although the period of peak intensity occurred from approximately 2.5 to 5 minutes.

In all cases, no attempt was made to calculate or measure the amount of heat absorbed by the test article. Rather, the applicable temperature was measured (in the case of the water cooled calorimeter, the difference in inlet verses outlet temperature and, in the case of insulated box and slug calorimeters, the temperature at the geometric center) to compare the full-scale tests to the certification tests. Since the goal was to compare the severity of the current certification test fire to a postcrash fuel fire this approach was determined to be acceptable.

The phase II series of tests were conducted in the Aircraft Component Fire Test Facility (Bldg. 287). Four propane burner nozzles were connected to a common supply header and arranged around the test article. The placement was optimized to ensure 100 percent flame coverage of the test article while maximizing the thermal exposure as measured by the associated temperatures. This arrangement is shown in figure 5. The three test articles were employed to characterize the fire threat. Each test utilized Type K thermocouples and the data were recorded in an Omega/AT&T data acquisition system.

The phase IV tests were also conducted at the Aircraft Component Fire Test Facility and utilized the same instrumentation as in phase II. The oven was a Model XL240 electric box furnace manufactured by the L&L Special Furnace Co. It was capable of producing temperatures up to 2350 degrees Fahrenheit and was equipped with a venturi to allow for purging combustion products. The interior dimensions were 25 inches wide, 27 inches high, and 37 inches deep. The furnace was equipped with a digital control system which allowed for temperature ramp rates and soak periods to be pre-programmed. The test setup is shown in figure 6.

SUMMARY OF TESTS.

PHASE I. A total of 11 full-scale tests were run under phase I. The first eight tests utilized the water calorimeter specified in ED56A. The results from a representative test, characterizing the fuel fire environment, are shown in figures 7, 8, and 9. In this test, maximum fuel fire temperatures ranged from 1800-1900°F (figure 7). The peak heat flux, as measured by a Gardon gauge calorimeter, ranged from 14-15 Btu/ft ^{2}-sec (figure 8). The temperature and heat flux were typical of a large jet fuel fire. Figure 9 shows the temperature rise (outlet temperature minus inlet temperature) history experienced by the water calorimeter. Water temperature increases approaching 140°F were measured. A comparison of figures 8 and 9 reveals a remarkable similarity between the heat flux, measured by the Gardon gauge, and the temperature increase,

measured by the water calorimeter. Obviously, the consistency in results indicates that the instruments are interchangeable. Also, since both the Gardon gauge and the water calorimeter are water-cooled, the measured data corresponds to the incident heating rate since surface radiation losses should be negligible.

The effect of the surface condition of the water calorimeter on the measured water temperature increase was examined. In one test the calorimeter was cleaned, using a surface grinder, to a bare metal shiny finish. In another test, the calorimeter was cleaned by hand with a wire brush and exhibited a dull finish that was clean of soot. Finally, a third test was conducted in which the calorimeter was uncleaned, leaving a fairly uniform thick layer of soot on the surface. Figure 10 shows the effect of surface cleaning on water temperature rise. Although the results are somewhat similar, it appears that a 15°F higher temperature rise may be achieved by the water calorimeter when the surface is cleaned with a wire brush as compared to when the surface is left uncleaned.

To validate the results from the water cooled calorimeter, the dry box and slug calorimeters were also subjected to the fuel fire. Figure 11 compares the internal temperature measured at the geometric center of the dry box and slug calorimeter. The heating profiles are very different due to the design and thermal properties of each device.

PHASE II. A total of 14 tests were conducted under this phase of the test program. The test setup is shown in figure 5. The first five tests of the series concentrated on attempting to replicate the data obtained from the full-scale fuel fires utilizing the water-cooled calorimeter. Various configurations of burners were tried as was varying the orifice size of the burners along with varying the gas pressure to the burners. Typical data are shown in figure 12. The maximum ΔT observed was 108°F for a short period of time. This came far short of our average 130-140°F ΔT observed in the phase I tests. It was evident that the propane burners could not be adjusted to produce the heating rates observed in the fuel fire, as measured with the water calorimeter.

The remaining tests in the series were set up in accordance with the specifications of ED56A, which required calibrating the flame with the water-cooled calorimeter set at a ΔT of 65.5°F. The calorimeter was then replaced with first the slug calorimeter and then the dry box calorimeter and traces of the internal temperature for each were obtained. This data is presented in figures 13 and 14 respectively.

PHASE III. A limited literature search was performed in an attempt to predict a realistic thermal profile for the postcrash fire environment. Obviously, no temperature data on real postcrash environments from accidents were found. Some experimental data were available but not in sufficient quantities to be representative of the postcrash environment. This was because of either varying test conditions or because fire-fighting efforts were initiated early on in the experiment. Several fires causing the destruction of either the data recorder or voice recorder have been fueled over a long period of time by natural materials. The Air Inter crash in Strasbourg, France, on January 20, 1992, and the Lauda Air crash in Suphan-Buri, Thailand, on May 26, 1991, are examples. Considerable work has been done in large natural-fuel fire characterization by the US Forestry Service. An experiment conducted by Philpot details results obtained from burning a 4.5 acre plot of natural fuel which totaled 750 tons or 8 pounds per square foot (reference 2). After 30 minutes all instrumentation measured temperatures less than 500°F.

PHASE IV. A series of three tests were run in this phase. All three tests were designed to assess the adequacy of the long-term/low-temperature (10 hours/260°C) fire test that is under consideration by EUROCAE. The first two tests were run utilizing the dry box calorimeter. The purpose was to assess instrumentation requirements and test protocol. The original EUROCAE proposal called for inserting the preconditioned test article into an oven that had been stabilized at 260°C. It was shown that the tests were not very repeatable when done in this manner, since the time to insert the test article varied depending on the ability of the person performing the task as well as ease of aligning the instrumentation. A subsequent revision to the EUROCAE proposed test has the test article placed in the oven with the oven at ambient conditions and then heating up both the oven and test article to 260°C. The warm-up time is limited to 2 hours. This protocol allows for much more repeatable tests and also increases the severity since the recorder is now exposed to high temperatures for up to 2 hours longer than the 10-hour test window. The third test utilized a current state-of-the-art magnetic tape cockpit voice recorder that was certified under TSO C-84; i.e., the recorder was compliant to fire test requirements comprised of exposure to flames of 2000°F enveloping at least 50 percent of the outside area of the case for 30 minutes. The purpose of this test was to ensure that a currently certified recorder would not pass the new proposed low-temperature/long-duration (260°C/10 hours) test criteria. Post-test inspection revealed that the recorder failed during the course of the 10-hour exposure at 260°C.

DISCUSSION AND ANALYSIS.

As discussed previously, fuel fire tests conducted during phase I yielded sustained ΔT's of approximately 120-140°F in the water calorimeter. These tests also yielded some interesting results regarding the assumed absorption factor used in ED56A. For the propane burner high-energy fire test, ED56A requires a heat transfer rate of 158 Kw/M sq. Converting to BTU/ft sq-sec yields;

$$(158 \text{ Kw/M sq}) / (11.35 \text{ Kw/M sq/BTU/ft sq-sec}) = 13.92 \text{ BTU/ft sq-sec}$$

This number agrees very well with the Gardon gauge calorimeter readings obtained in the fuel fire tests (figure 8). Back calculating, using the equation in ED56A to find the required Delta T to produce 158 Kw/M sq for the flight data recorder sized water calorimeter used in our test, yields a result of;

$$158000 \text{ W/M sq} = \frac{(\text{Delta T})(0.189 \text{ Kg/s})(4187 \text{ J/Kg/Deg C})}{(0.365 \text{ M sq})(0.5 \text{ [absorption factor]})}$$

Solving for Delta T yields;

$$\text{Delta T} = \frac{(158000 \text{ W/M sq})(0.365 \text{ M sq})(0.5 \text{ [absorption factor]})}{(0.189 \text{ Kg/s})(4187 \text{ J/Kg/Deg C})}$$

$$\text{Delta T} = 36.44 \text{ Deg C or } 65.59 \text{ Deg F}$$

Fuel fire tests produced an average ΔT of about 130°F at the peak of the fire. This would indicate that either the fire is producing nearly double the assumed 158 Kw/M sq flux or the absorption factor assumed in ED56A is not correct. Since the Gardon gauge heat flux data correlated very well with the fire output of 158 Kw/M sq, it would appear that the absorption factor assumed is not conservative and should be more on the order of 1 (versus 0.5).

The dry box and slug calorimeters were also subjected to the fuel fire in an attempt to verify this data. Based on previous work (reference 3), the heat transfer to an object immersed in a flame can be altered due to its thermal mass or by forced cooling of the object. Since the water calorimeter is continuously cooled while in the flames, there was concern that the disparity in results as compared to the ED56A expected results may have been due to this phenomenon. The dry box exterior shell, being constructed of relatively thin carbon steel, was expected to heat up to flame temperature in a rapid manner. The slug, being very thermally massive, could result in the surface heating up to flame temperature in a relatively longer time frame than the dry box. The surface of the water cooled calorimeter would stay relatively cold when compared to the adjacent flame temperature. Figures 15 and 16 compare the fuel fire and propane burner heating conditions in terms of the internal temperature history of the slug calorimeter and dry box calorimeter, respectively. The comparison was made over a period of 6-8 minutes, or at the point in time when it appeared that the heating rate (temperature slope) began to decrease due to the diminishing fuel fire. It is evident that both calorimeters heat up faster in the fuel fire than in the propane burner. The internal temperature is approximately 40 percent higher when the calorimeters were subjected to the fuel fire exposure. Using the water calorimeter the difference in heating rate was determined to be about a factor of two (water temperature rise of 130°F vs. 65°F in the fuel fire and propane burner, respectively). Heat losses from the hot surface temperature of the slug and dry box calorimeters may account for the difference in apparent heating rates between the cooled water calorimeter and the uncooled slug/dry box calorimeters.

The propane burner test method was evaluated to determine how it could be enhanced to ensure that the test article was being tested at a severity level consistent with the fuel fire data from phase I. It was not possible to modify and/or adjust the propane burners to create the heating conditions measured by the water calorimeter in the fuel fire. Therefore, it was concluded that the easiest way to subject the recorder to the same overall total heat flux was to double the time of exposure.

One of the concerns with the current fire test requirements specified in the Technical Standard Orders (TSO's) is the belief that the test protocol is written too loosely, thus allowing for some interpretation while performing the testing. Also, by allowing for different fuels and calibration methods to be used, uncertainties are introduced when different laboratories perform the testing. For the TSO-required testing to be most effective it must be conservative, simple, repeatable, and reproducible. While it would appear that performing a single test that combines both the high intensity (2000°F/30 minutes) and low intensity (500°F/10 hours) exposure conditions would be the desirable thing to do, there exists two concerns with that approach. First, insufficient data exist to determine a "typical" postcrash temperature profile. Any profile developed would be somewhat subjective. Second, combining the two separate exposure tests would require a strict test protocol and/or special equipment to be able to perform the test with the required within laboratory repeatability and between laboratory reproducibility. Allowing for two exposure tests to be run independently simplifies the test methods and does not require the procurement of expensive test equipment. The increase in repeatability/reproducibility offsets any gain from performing a combined test. From the limited literature search that was performed it is concluded that the proposed 500°F temperature for the long term/low intensity fire test will envelope the temperature regime produced by a smoldering fire comprised of natural materials.

MAJOR FINDINGS.

1. The heat exposure condition produced by the current propane burner fire test for flight recorders is not as severe as a jet fuel fire.

2. It was not possible to modify and/or adjust the propane burners to raise the heating conditions measured by the water calorimeter to the level experienced in a jet fuel fire.

3. Doubling the exposure time of the propane burner test to 60 minutes appears to be the most feasible approach for ensuring that a flight recorder is exposed to the same integrated heating as a 30-minute postcrash fuel fire.

4. Currently certified magnetic tape flight recorders will not survive the proposed 10-hour exposure at 500°F.

5. Based on limited data it appears that the proposed 500°F long term temperature test will ensure that flight recorders will survive postcrash smoldering fires involving natural materials.

6. There exists insufficient data to be able to define a "typical" post-accident temperature profile for a flight recorder exposure.

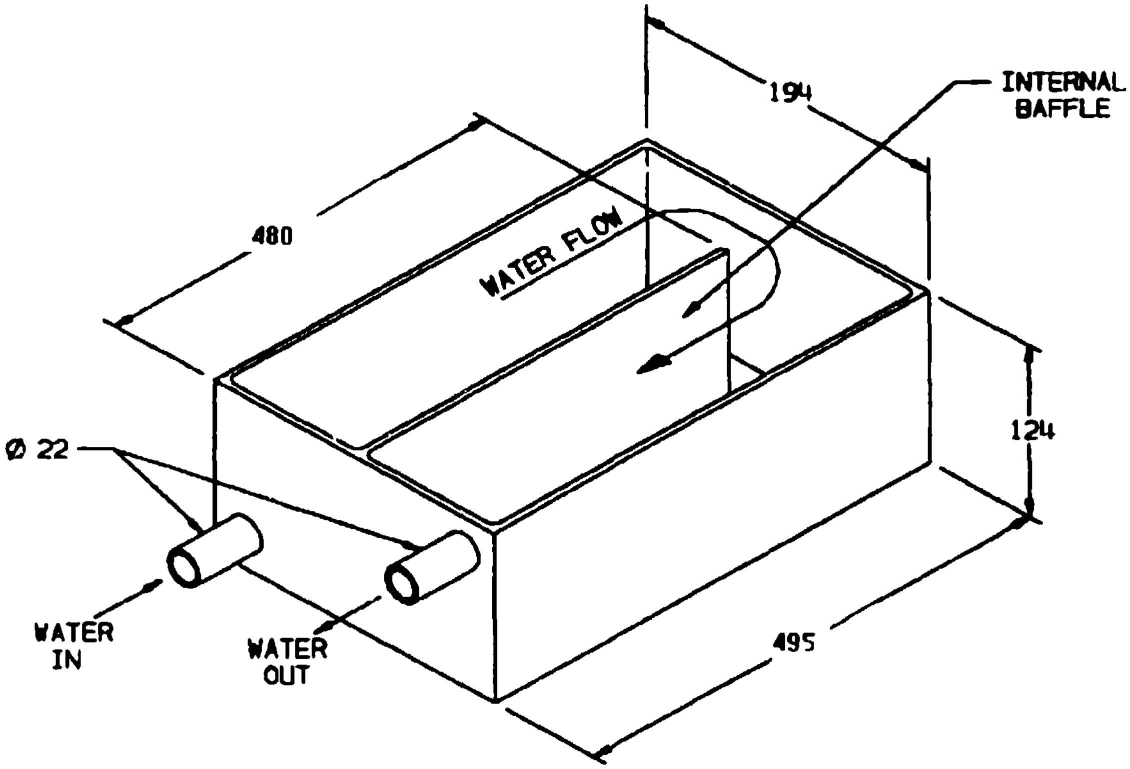
7. The repeatability and reproducibility of flight recorder fire-testing will be greater by having two separate tests (i.e., a short-term/high-intensity test and a long-term/low-intensity test) rather than by having a single-profile test.

REFERENCES.

1. Minimum Operational Performance Specification (MOPS) for Cockpit Voice Recorder Systems, EUROCAE Council, Document EUROCAE ED56A.

2. Philpot, C.W., "Temperatures in a Large Natural-Fuel Fire", US. Forestry Service, Pacific Southwest Forest and Range Experimental Station, Berkeley, CA., Research Note PSW-90.

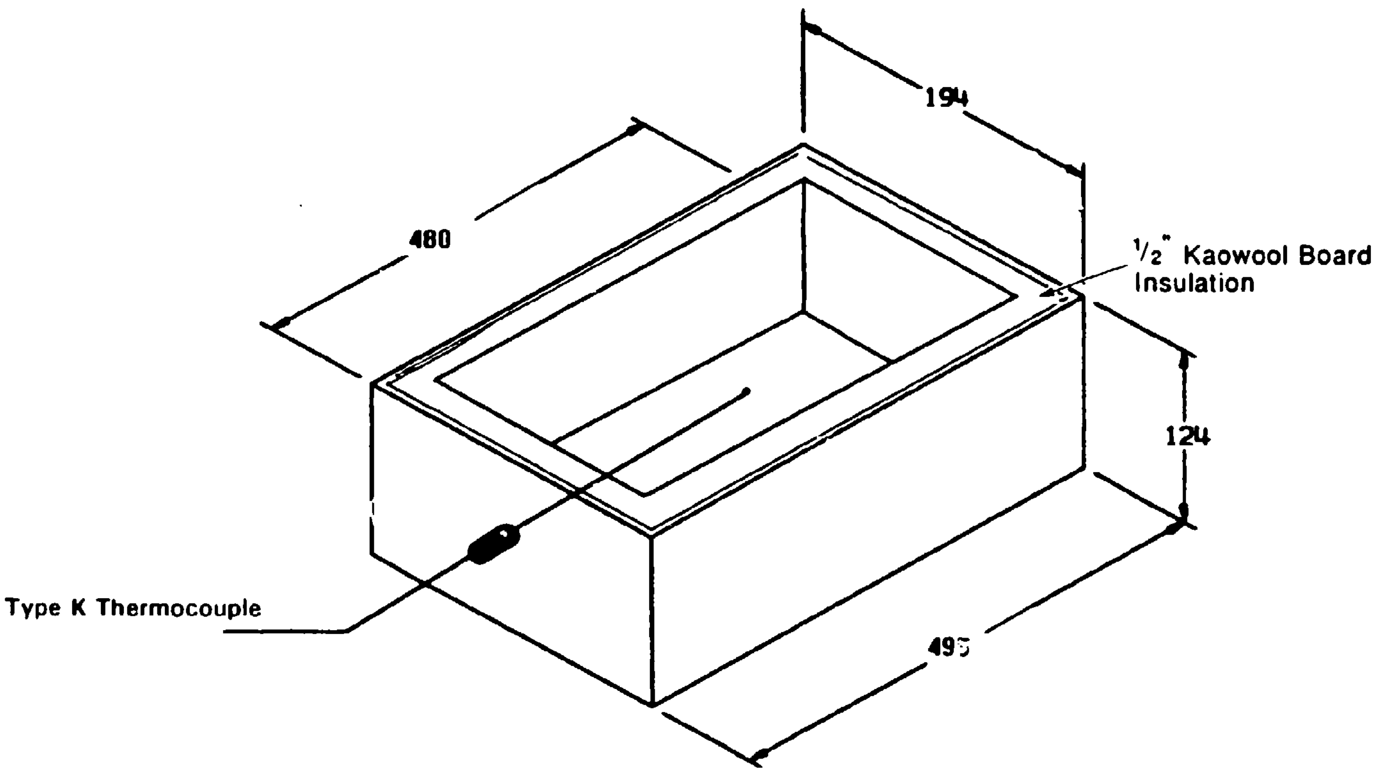
3. Keltner, N.R., Nicolette, V.F., Brown, N.N., and Bainbridge, B.L., "Test Unit Effects in Heat Transfer in Large Fires", Journal of Hazardous Materials, Vol. 25 (1990), pp. 33-47.



NOTES:

a. Top removed for clarity
b. Material is 1.6mm mild steel
c. Dimensions in millimeters

FIGURE 1. WATER CALORIMETER



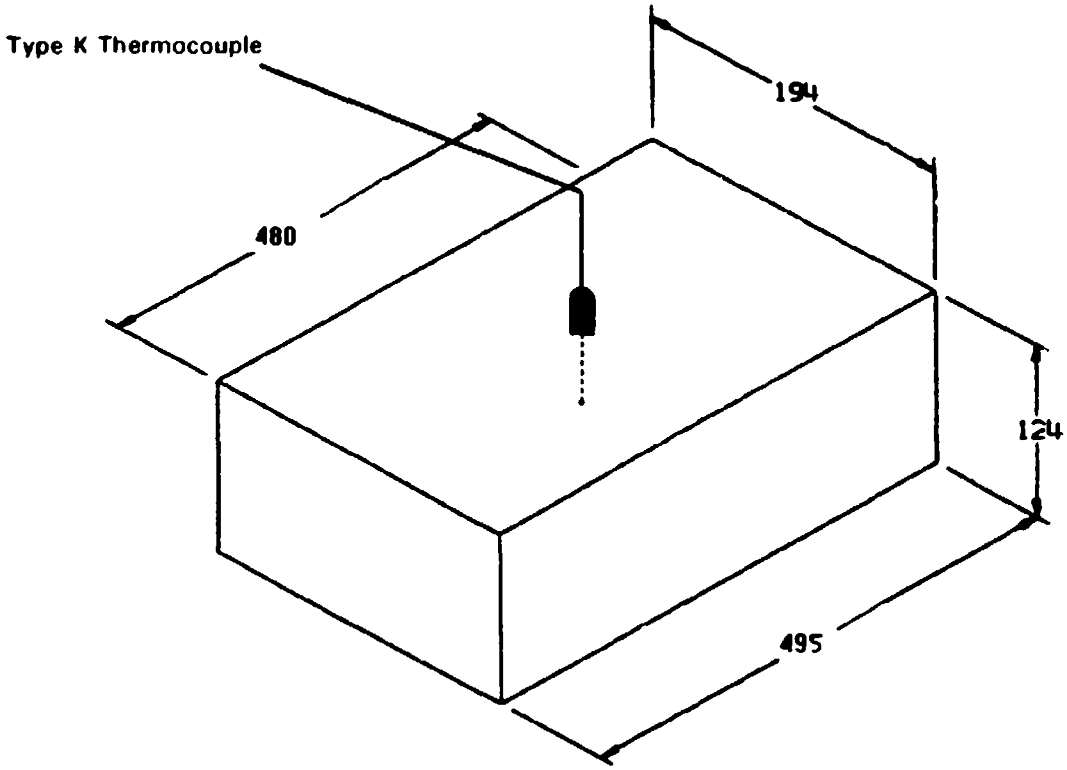
NOTES:

a. Top removed for clarity

b. Material is 1.6mm mild steel

c. Dimensions in millimeters

FIGURE 2. DRY INSULATED BOX



NOTES: a. Material is mild steel
b. Dimensions in millimeters

FIGURE 3. SOLID STEEL SLUG CALORIMETER

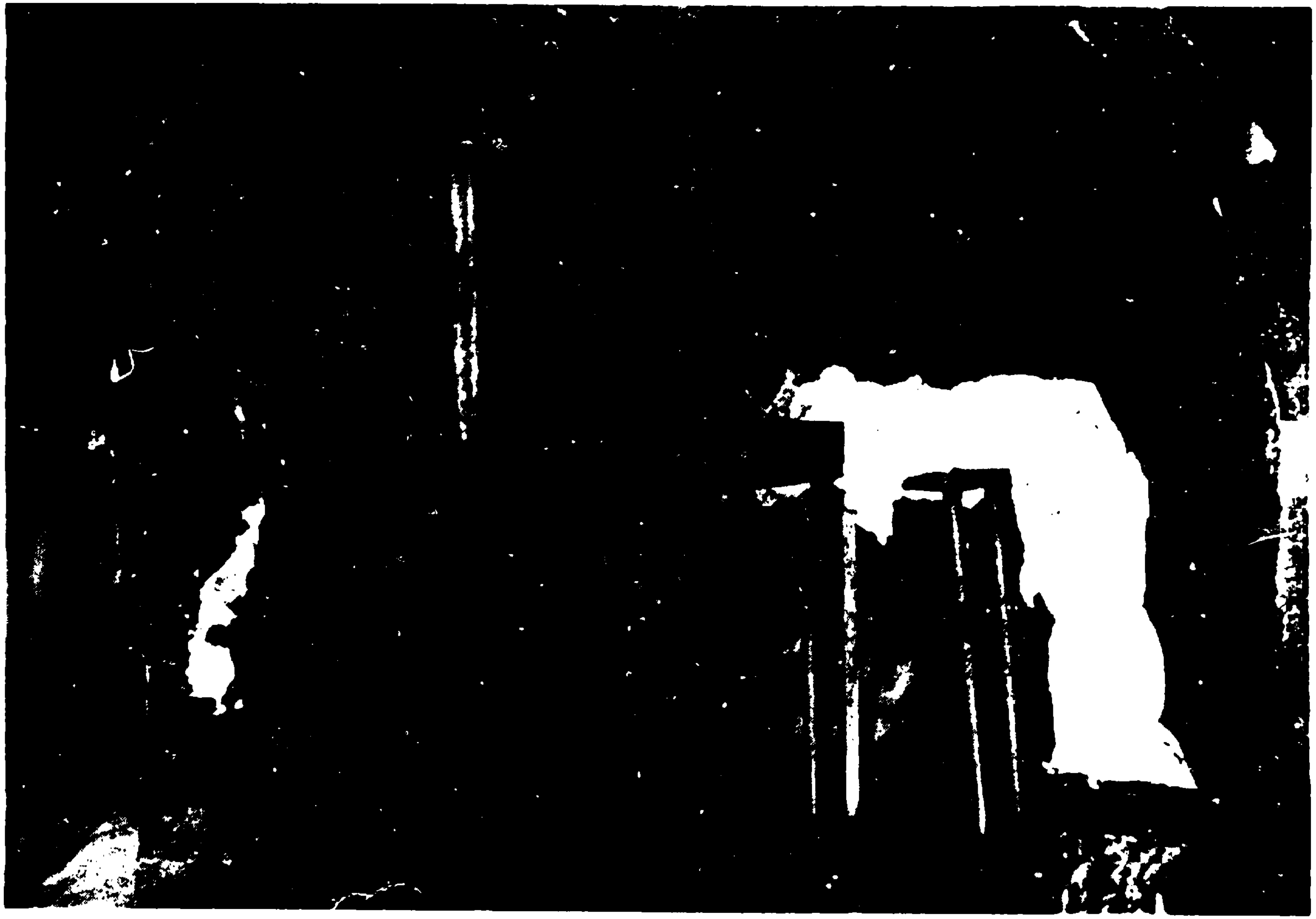


FIGURE 4. FULL-SCALE TEST SETUP

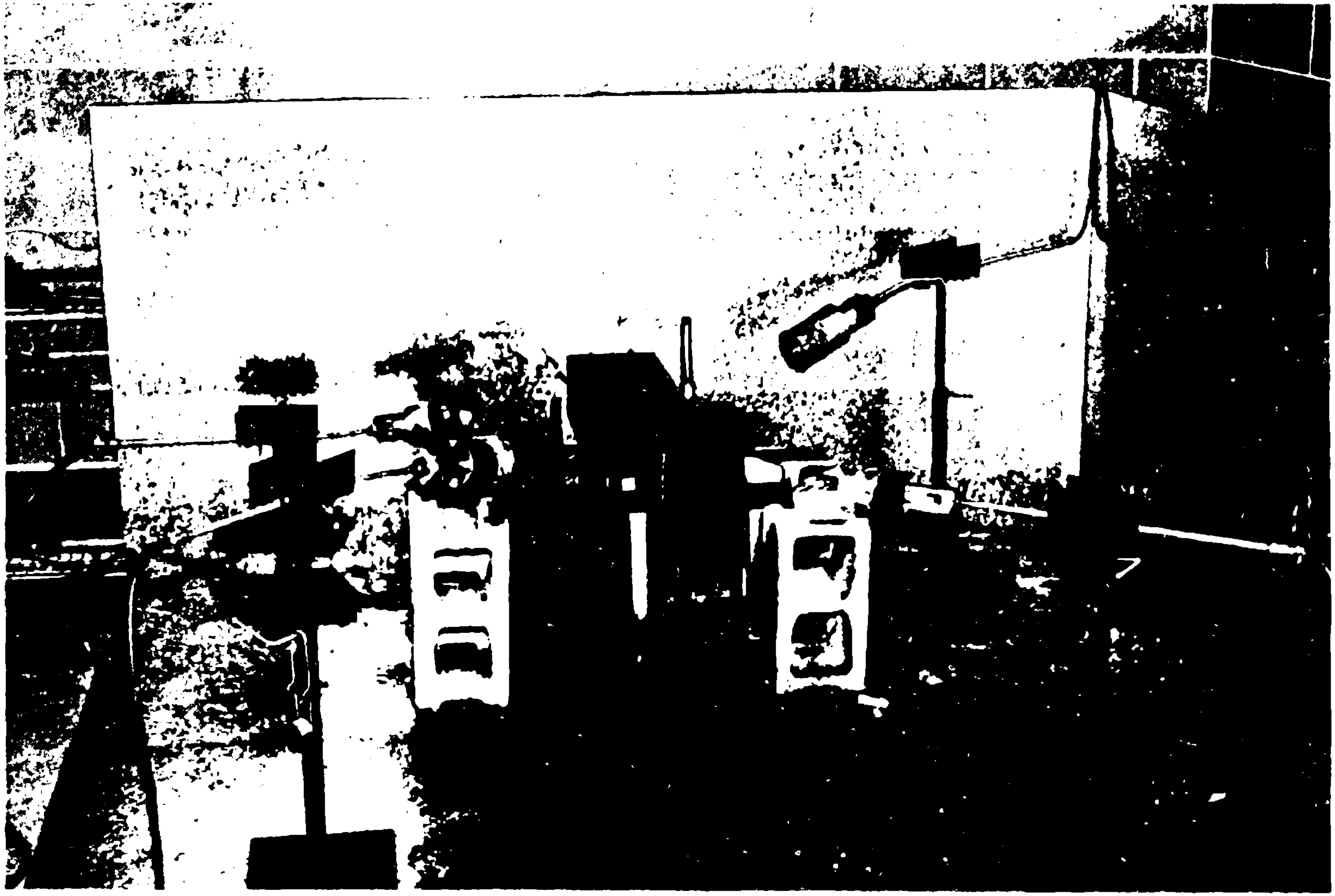


FIGURE 5   PROPANE BURNER TEST SETUP

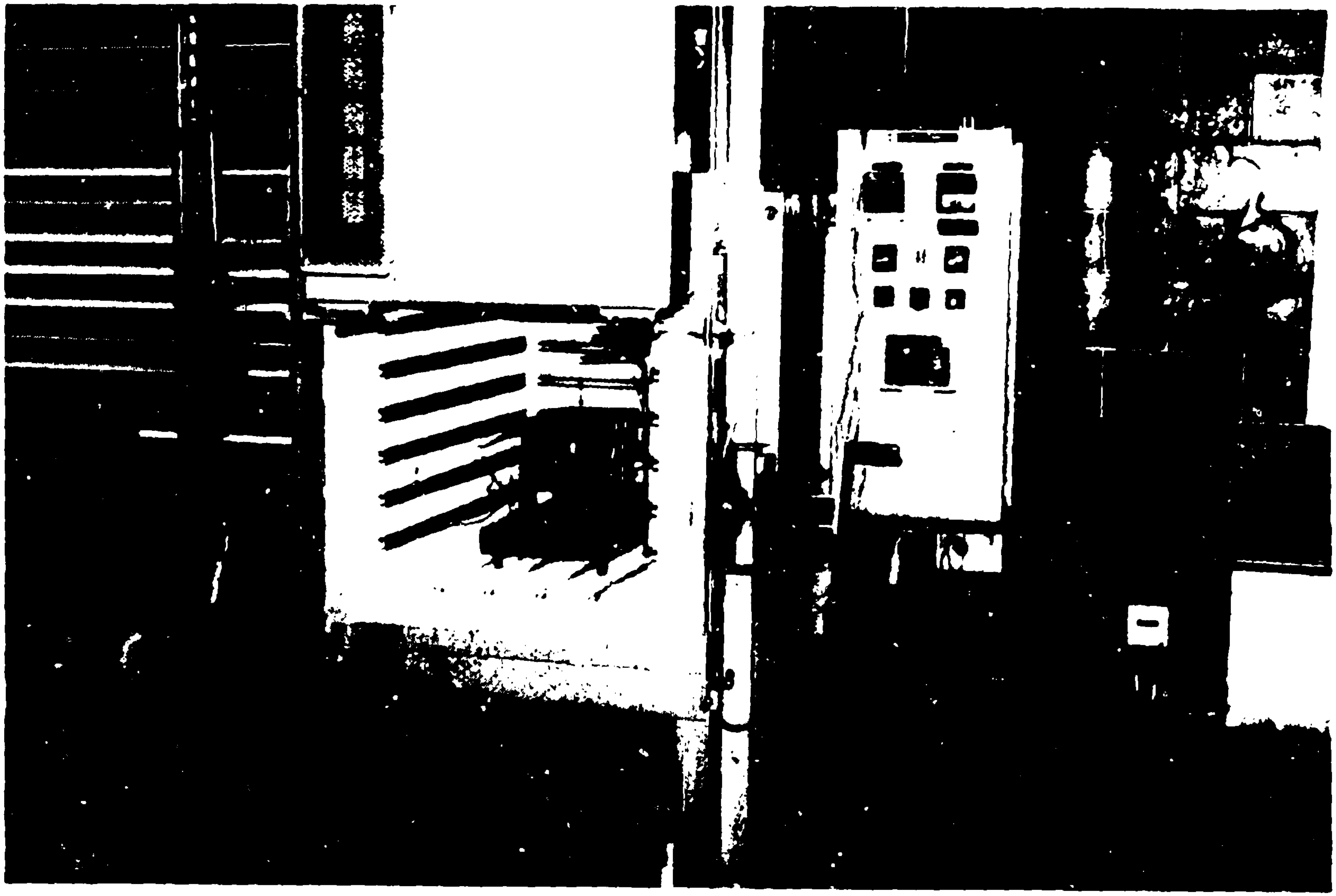


FIGURE 6. LOW-TEMPERATURE FIRE TEST SETUP

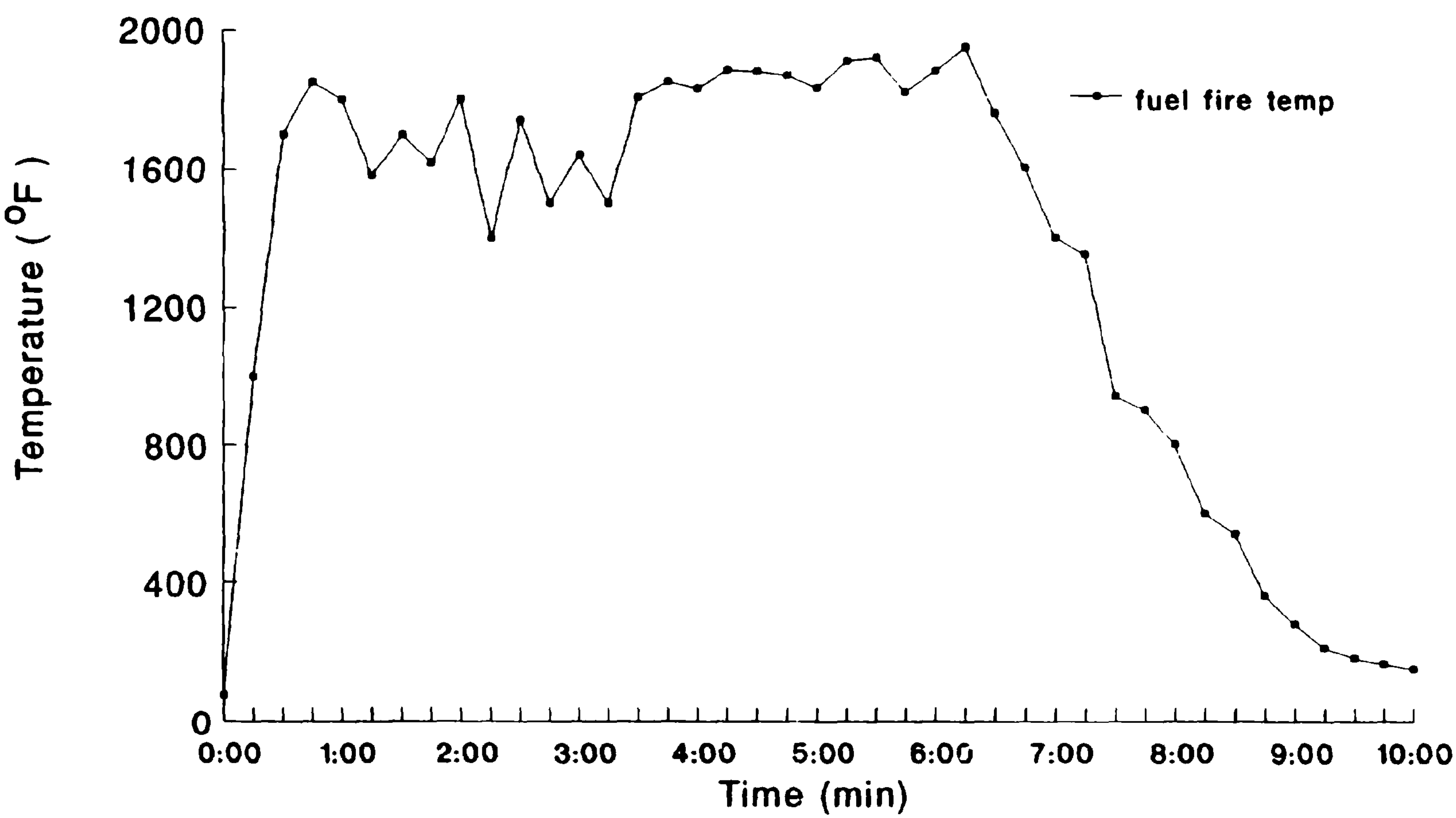


FIGURE 7. FUEL FIRE TEMPERATURE

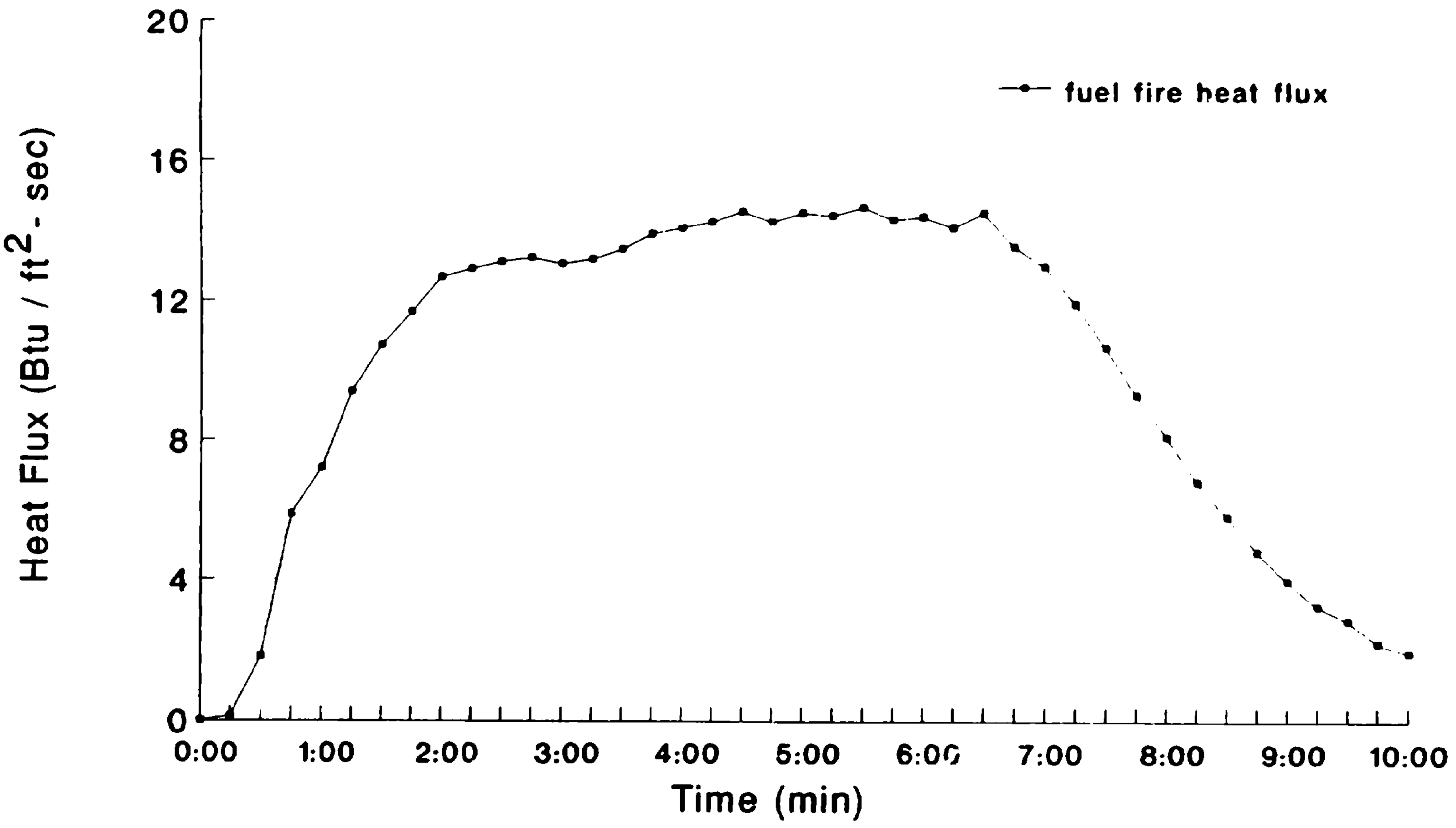


FIGURE 8. FUEL FIRE HEAT FLUX

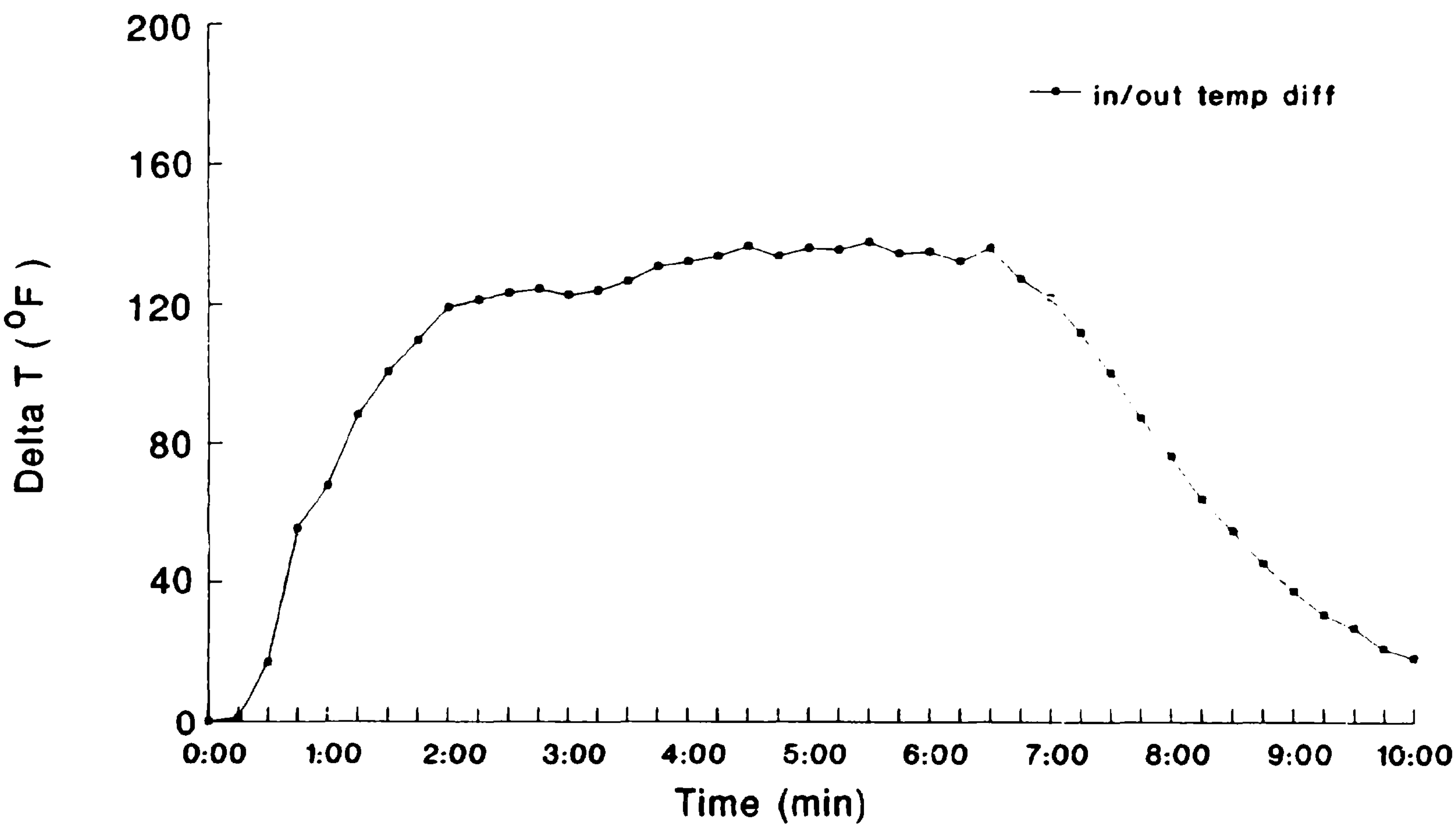


FIGURE 9. FUEL FIRE WATER CALORIMETER TEMPERATURE INCREASE

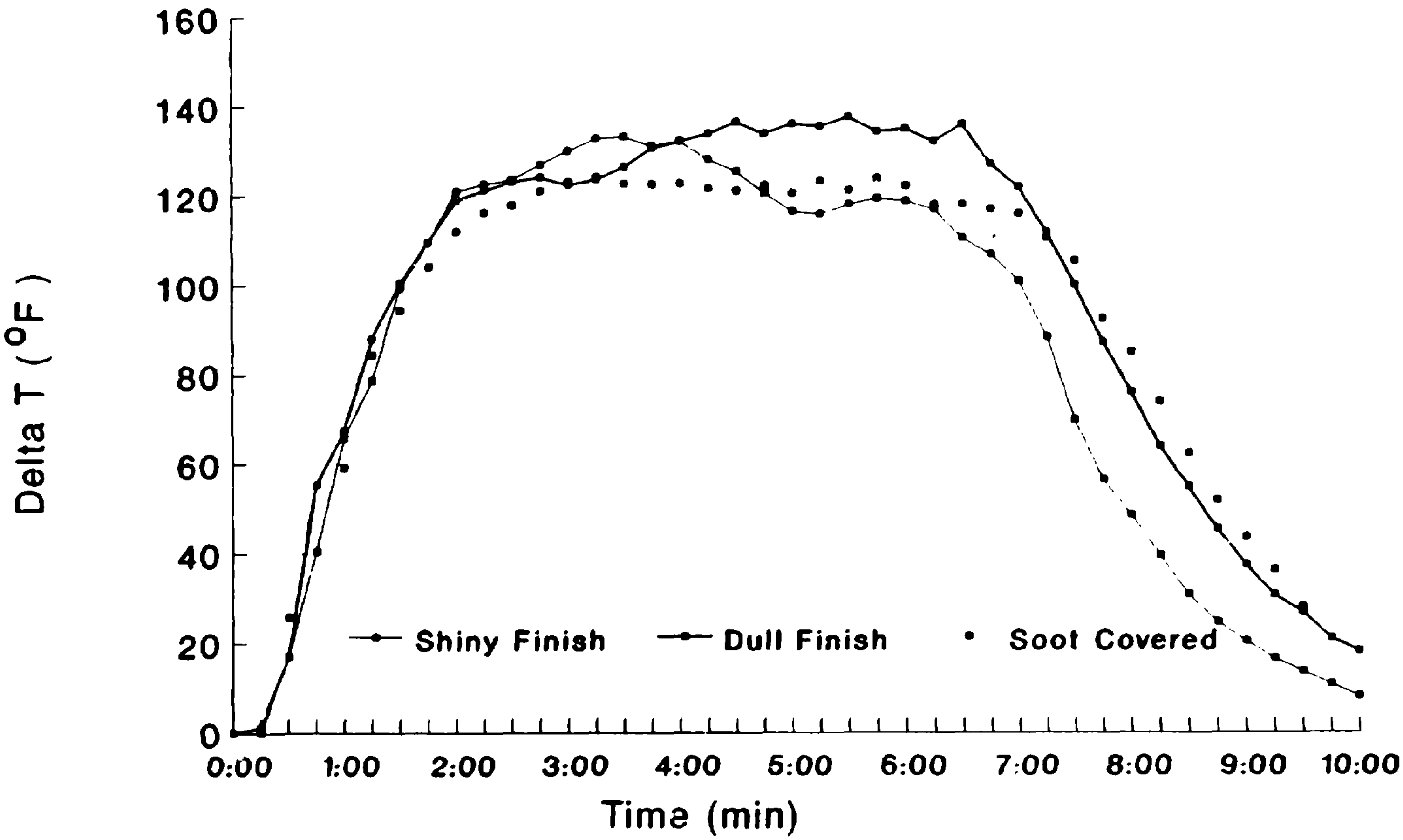


FIGURE 10. SURFACE CONDITION EFFECT ON WATER CALORIMETER IN FUEL FIRE

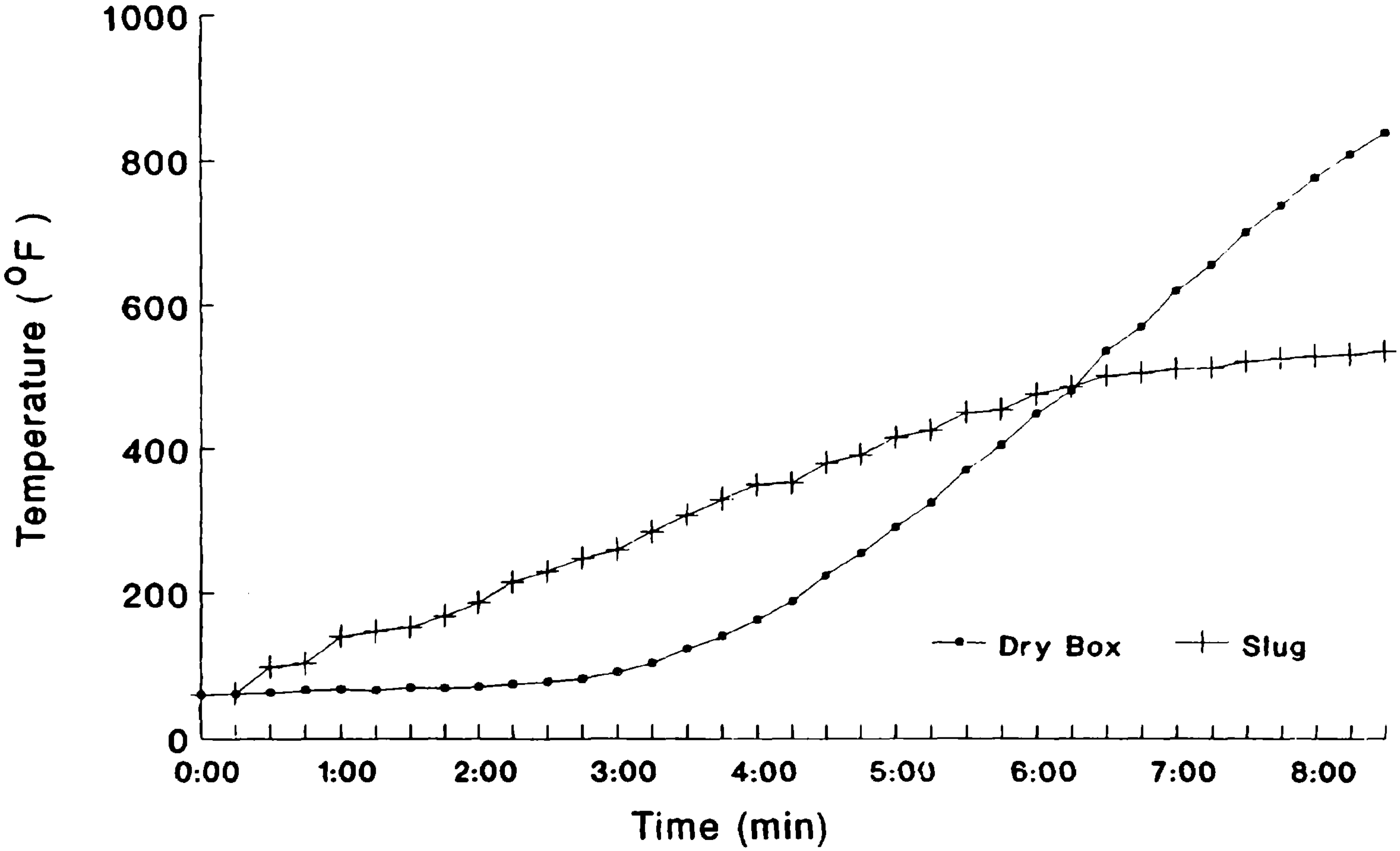


FIGURE 11. INTERNAL TEMPERATURE OF DRY BOX AND SLUG CALORIMETER IN FUEL FIRE

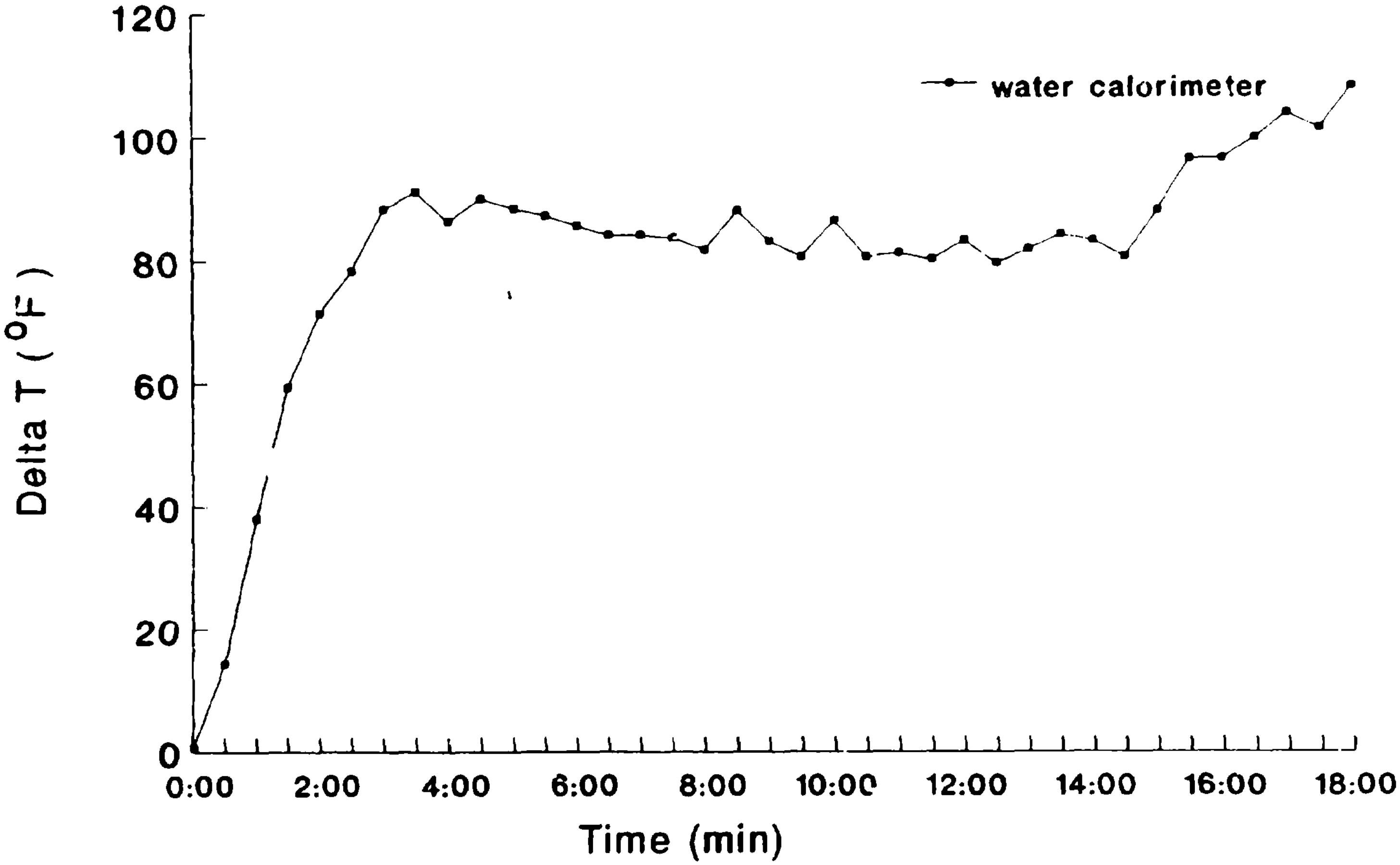


FIGURE 12. PROPANE BURNER WATER CALORIMETER TEMPERATURE INCREASE

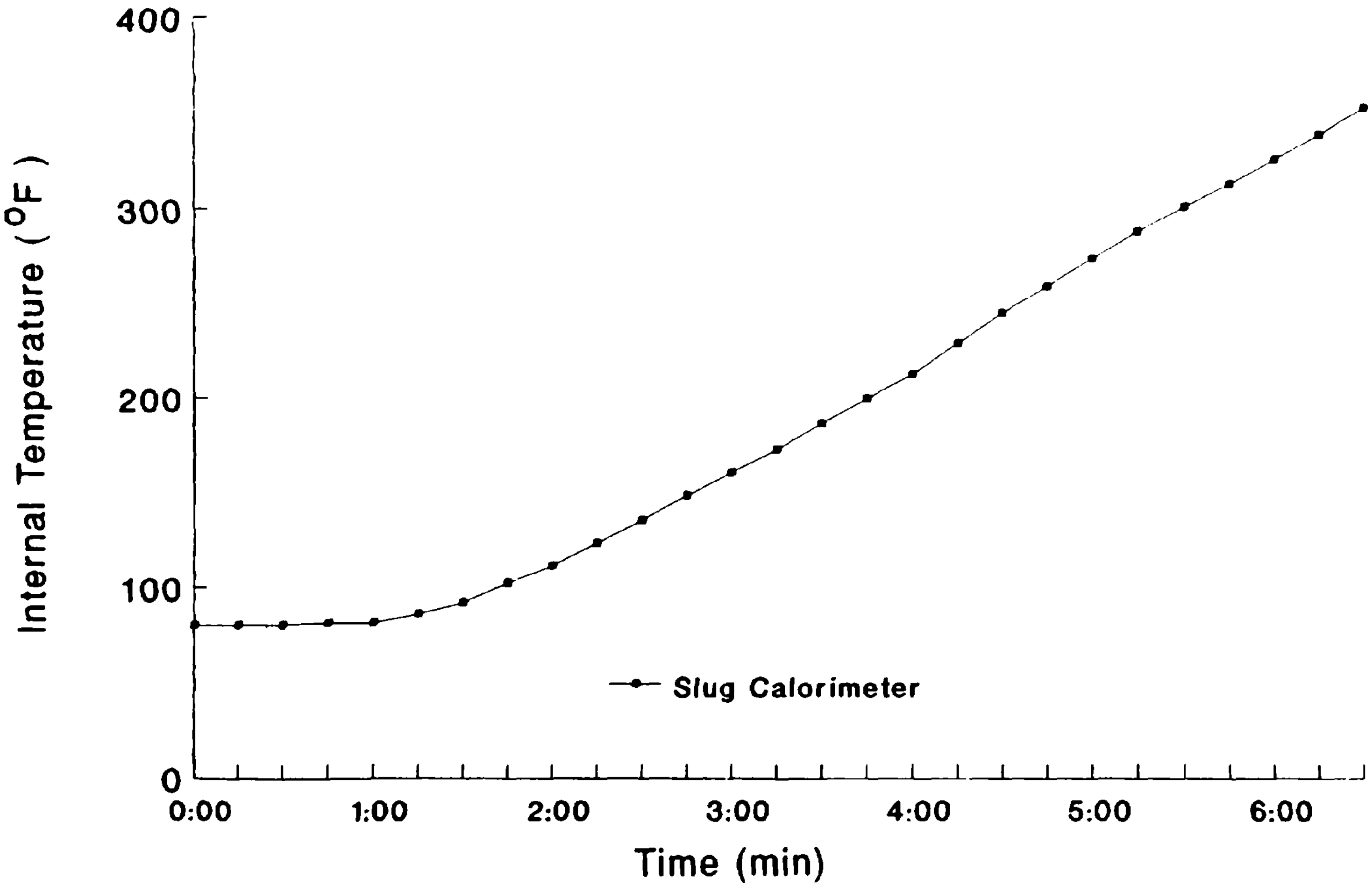


FIGURE 13. INTERNAL TEMPERATURE OF SLUG CALORIMETER IN PROPANE BURNER

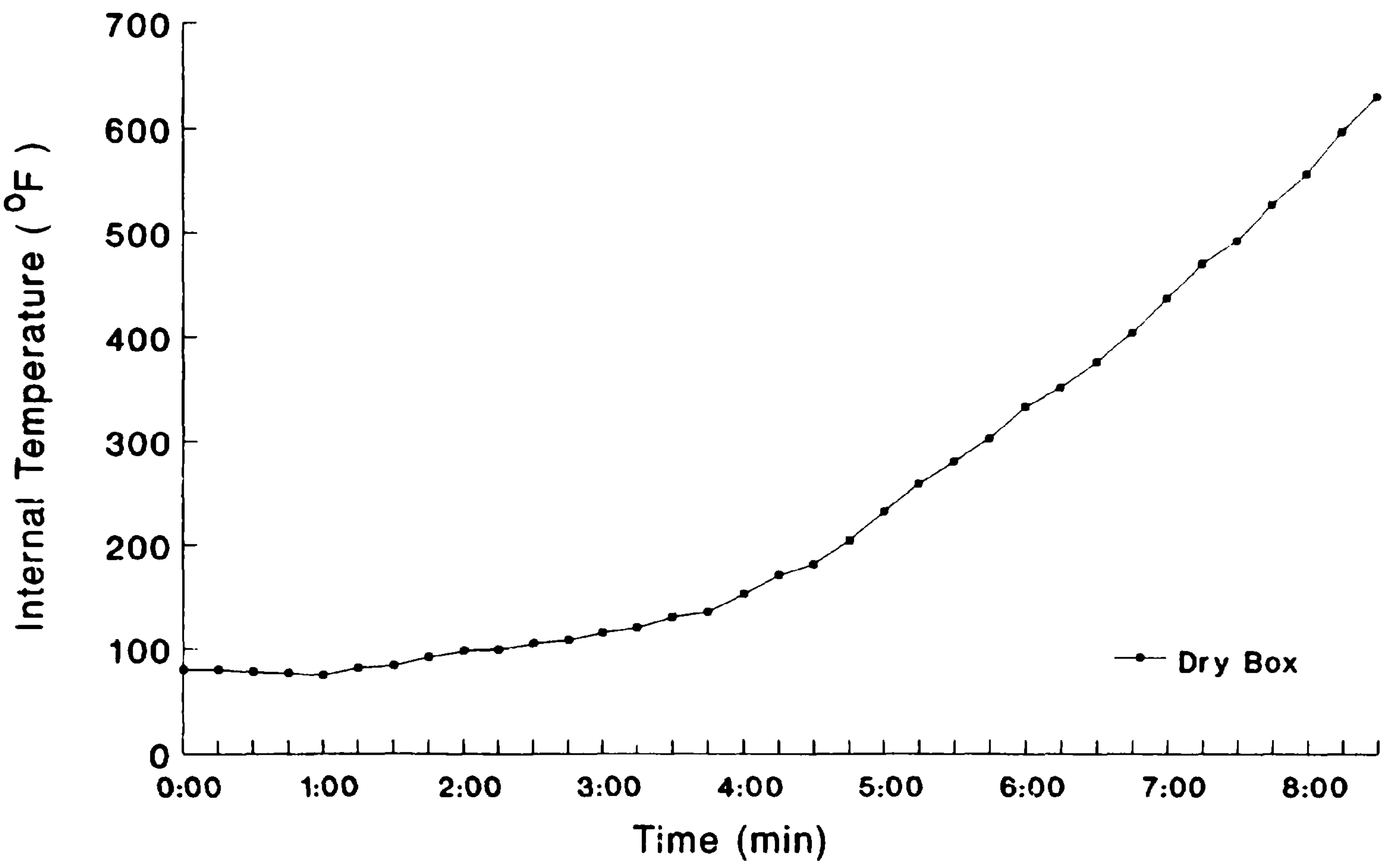


FIGURE 14. INTERNAL TEMPERATURE OF DRY BOX IN PROPANE BURNER

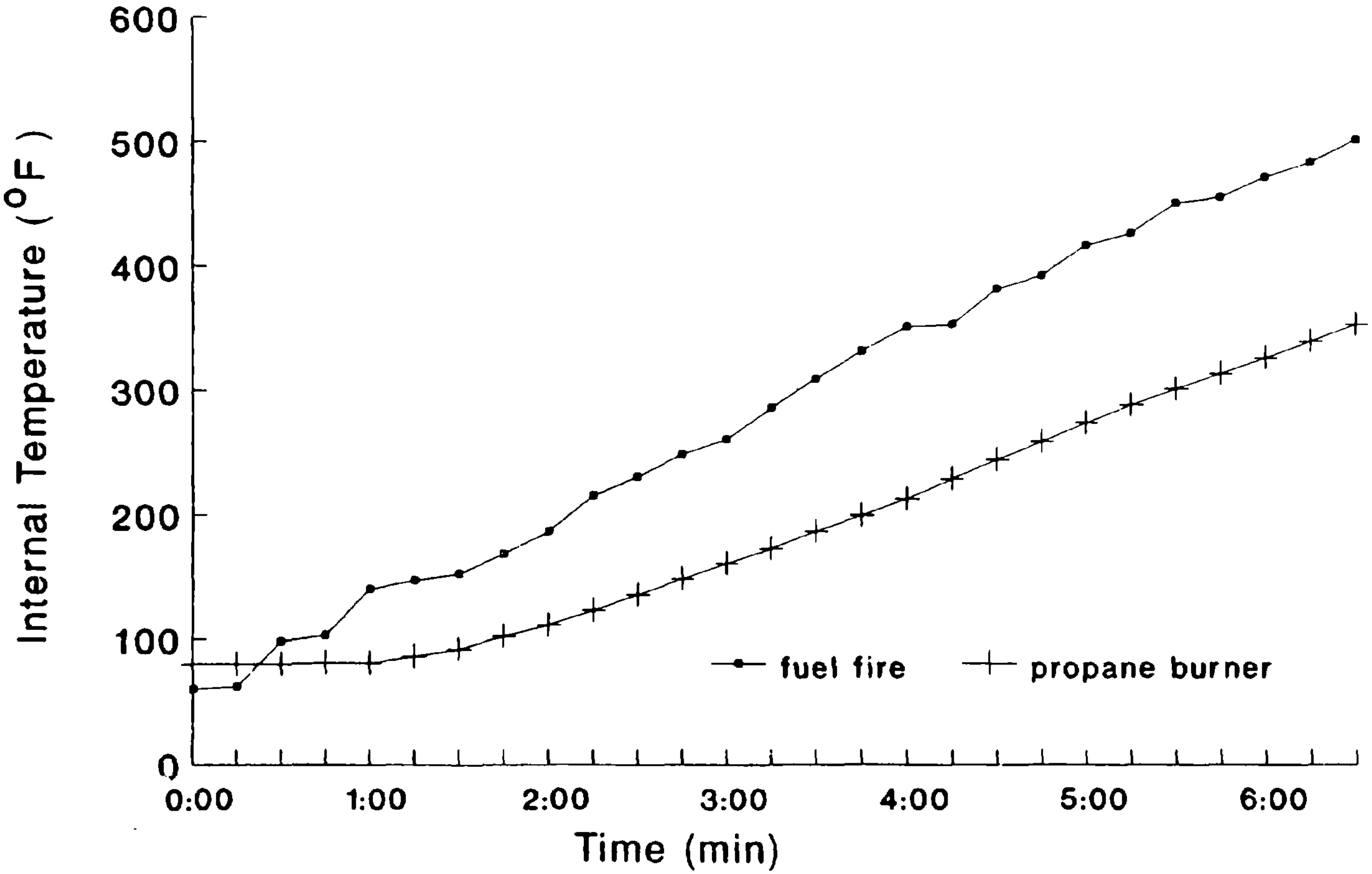


FIGURE 15. SLUG CALORIMETER TEMPERATURE IN PROPANE BURNER VS. FUEL FIRE

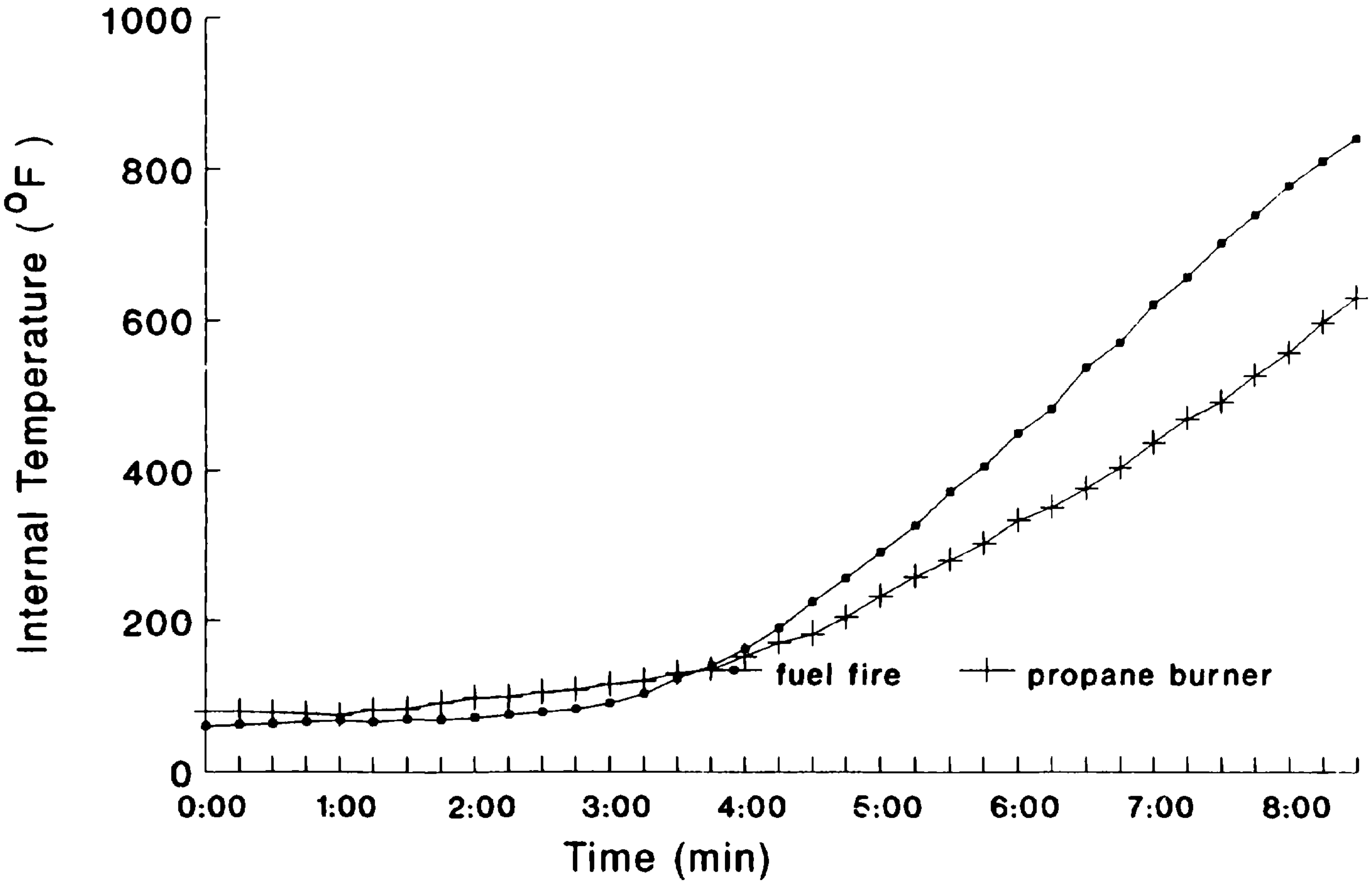


FIGURE 16. DRY BOX TEMPERATURE IN PROPANE BURNER VS. FUEL FIRE